FUNCTION-ORIENTED MATERIAL DESIGN OF JOINTS FOR ADVANCE ARMORS UNDER BALLISTIC IMPACT

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ABSTRACT

The objective of this research is to develop a system of software tools based on a new design methodology for the efficient composite armor structural design under ballistic impact loading conditions with a special focus on the joints design. An innovative design methodology, Function-Oriented Material Design (FOMD), is extended for the joint design problem of composite armor. The FOMD process includes the fundamental ballistic impact analyses of the composite armor, function analyses and targets setting of the joints, algorithms of the optimal design process, the design optimization of the joints, and evaluation of the new designs. The performance of a nominal joint design is virtually evaluated using LS-Dyna3D, which provides loading and boundary conditions for the optimal design process of an advanced joint. An integrated design environment developed on the basis of FOMD enables quick design process and user interaction. The final goal of this research is to develop an efficient design tool to lay out new joint concepts that improve the structural performances and prevent the early damage of the joints under ballistic impacts. An example design obtained is evaluated using the virtual prototyping, and it can be tested with the rapid prototypes developed in this research. Other design objectives, such as manufacturability and reliability of the design, will also be considered in the future.

1. INTRODUCTION

Extensive attention has been paid on ballistic impact simulation and composite armor design with the development of advanced material models and simulation software. However, at the current stage, efficient design methods for armor and related structures still need to be developed despite of a large number of simulation codes that have been available. In this research, design tools are developed to address this issue. With possibility of extension to composite armor design itself, this work is concentrated on the design of joints for composite armor. As with the use of other composite materials, connections (or so-called joints) of a composite armor with the other structural parts, e.g., a metal frame in a military vehicle, are among the weakest locations in the structure. The joint design for composite armors is no doubt a great challenge for the advanced army vehicles. State-of-the-art researches exclusively deal with simple metallic or composite joints under static and low-speed loading conditions. The performances of these joints under ballistic impact are not well understood, and the design problem of the joints for advanced composite armors has not been adequately addressed.

1.1 Advanced Composite Armors

Advanced composite armors (ACAs) are usually multi-layers consisting ceramic material, fiber-reinforced polymers, metallic screen, and possibly rubber materials. (Fink, 2002) These layers serve specific purposes in defeating projectiles and maintaining structural integrity of the armor as well as the rest vehicle structures. The outmost layer of the ACA is usually fiber reinforced polymers for the purpose of maintaining structural integrity. Ceramic material in the next layer has functions such as destroying the tip of the projectile, distributing the impact load over a large area of the composite, and decelerating the projectile. The inner composite layers support the ceramic and perform other functions such as holding the ceramic debris together and further resisting the projectile. The performance of each layer significantly influences the overall performance of the armor. (Fink, 2002; Kaufmann et al., 2003)

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **00 DEC 2004**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE
Function-Oriented Material Design Of Joints For Advance Armors Under Ballistic Impact

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Mechanical Engineering, The University of Michigan Ann Arbor, MI 48109; MKP Structural Design Associates, Inc. Ann Arbor, MI 48104

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001736, Proceedings for the Army Science Conference (24th) Held on 29 November - 2 December 2005 in Orlando, Florida. , The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**8**	

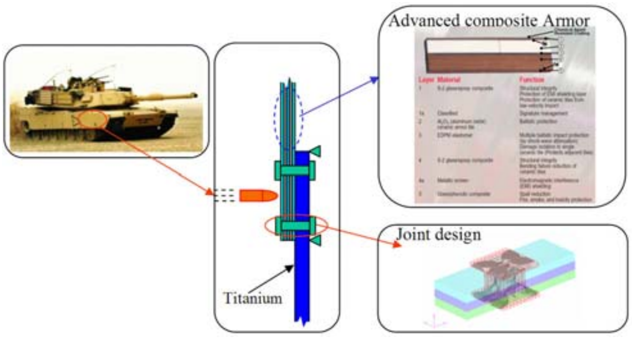


Figure 1. A joint design with quasi-static and ballistic concerns.

Previous studies regarding the composite armor design have considered material types and dimensions, such as thickness, as design variables. (Kurtaran et al., 2003) Very little research, however, can be found on the subject of joint design for composite armors. In this paper, we consider a design problem shown in Figure 1. It is seen in Fig.1 that the connection between ACA and metal structure is critical in the sense that ACA may fall off if the connection is damaged due to static, dynamic or ballistic loads. It is found in this research that different ACA designs can significantly influence the performances of the joints.

This paper concentrates on a joint design between an advanced composite armor and a vehicle structure. A design process is developed based on FOMD, and effectiveness of the design tools is demonstrated with virtual and rapid prototyping of an example joint. We investigate influences of the two different layouts of a composite armor on the performances of joints, especially, under ballistic impacts. The objective is to layout the optimum joints in terms of their sizes and shapes in order to maintain the structural integrity as well as improve the other performances of the ACA. It is found that both armor configuration and joint design have great impacts on the overall performances of the armor.

1.2 Function-Oriented Material Design (FOMD)

The design methodology utilized in the proposed research is referred to as *function-oriented material design* (FOMD). FOMD was developed based on a breakthrough technique for the topology optimization of structural systems developed by Bendsøe and Kikuchi in 1988 (Bendsøe and Kikuchi, 1988) and known worldwide as the *homogenization design method*. With advanced optimization techniques, such as multi-domain and multi-step optimization methods, FOMD has extended capabilities for a wide variety of engineering problems, and has been successfully applied to design vehicle structures with improved static, NVH, and crashworthiness performances.

An example is given in Figure 2 using the FOMD, which can be utilized in the research for lightweight yet strong structures for ballistic protection. In the example, the intermediate structure between stiff tiles (such as those in a composite armor) and soft skins (inside crew compartment) can be designed with functionally gradient properties and to be lightweight and high-performance. The intermediate structure improves the compatibility of very stiff tiles and soft skins, and thus can help to defer delamination and to improve strength of the whole structure.

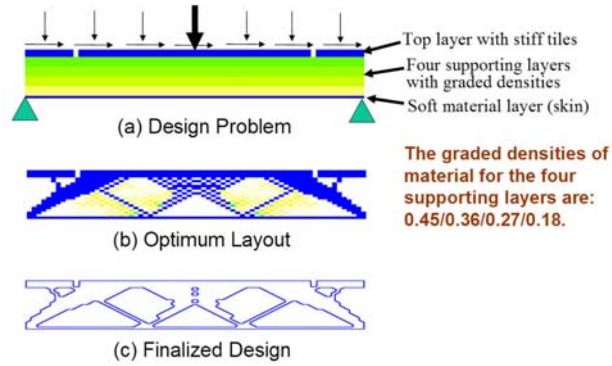


Figure 2. Lightweight functionally gradient structure design with stiffness/strength requirements

1.3 Design Strategy for Joints between Armor and Main Structure

Although testing is currently the major part of advanced armor design process, virtual prototyping is gradually accepted as an alternative tool for armor design because of the advances in material models and simulations codes. In this research, virtual prototyping is employed for conducting the design and verifying the resultant results. Experiments will be considered as a final tool for the proof of concept and to determine the actual advantages of the improved new designs. Related software tools for assisting physical prototyping are developed, and then have been integrated into the system to form a complete simulation and design system.

The design procedure is explained in the following Figure 3. As the first step, the system virtual prototyping is conducted with commercial code (LS-Dyna3D). The potential problems with the nominal joint (bolt) design are evaluated. Then, design objectives, variables, loads, and constraints are defined. With these, the design problem is constructed, and optimal design is obtained. The new design is also evaluated using LS-Dyna3D, and it can be further tested using the prototypes fabricated in this research with rapid prototyping technique. In each

design cycle the performances of the joint can be improved using the topology optimization, and this process can be iterated until a suitable design is obtained.

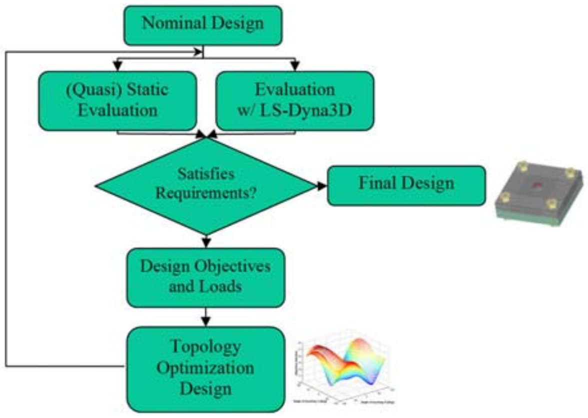


Figure 3. Design loops of ACA joints

2. MATERIAL MODEL

2.1 Ceramics Model

The most widely used material model for ceramics is Johnson-Holmquist (JH2) ceramics model. (Johnson and Holmquist, 1999) This model has been implemented in several commercial software, including Epic, Autodyn, and LS-Dyna3D. This model is widely used in armor simulation and design, and many reports can be found in literature. (e.g. Holmquist and Johnson, 2002; Cronin et al., 2003; Yen, 2002; Zaera et al. 2000) LS-Dyna3D is selected as the simulation tool because of its advantage as the most widely used general-purpose code for the problem. Many advanced material models and numerical methods are available in LS-Dyna3D. The material model (JH2) is named as material 110 (*MAT_JOHNSON_HOLMQUIST_CERAMICS). Material parameters are adopted from literatures for the current research. Silicon carbide (SiC) is selected as the ceramic material, and material parameters are given as:

$$\rho = 3163\,Kg/m^3,\ \ G = 183\ GPa,$$
$$A = 0.96,\ \ B = 0.35,\ \ C = 0.0,\ \ M = 1.0,\ \ N = 0.65,$$
$$Ref\ \ Strain\ Rate\ (EPSI) = 1.0,\ \ Tensile\ Strength = 0.37GPa,$$
$$Normalized\ \ Fracture\ Strength = 0.8,$$
$$HEL = 14.567\,GPa,\ \ HEL\ \ \mathrm{Pr}essure = 5.9GPa,$$
$$HEL\ \ Strength = 13.0GPa,$$
$$D_1 = 0.48,\quad D_2 = 0.48,$$
$$K_1 = 204.785GPa,\ \ K_2 = K_3 = 0.0,\quad \beta = 1.0,$$

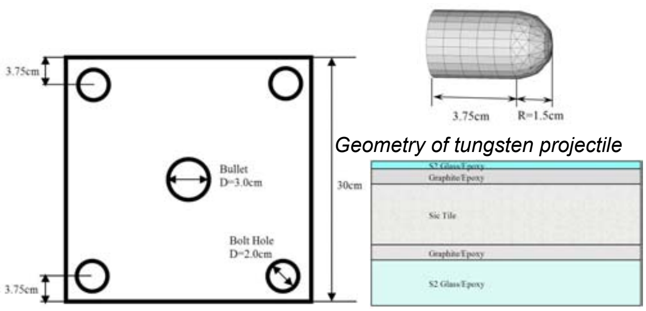
2.2 Fiber Reinforced Polymers (FRPs)

The same material model in Yen et al. (Yen, 2002) was selected for fiber reinforced polymer layers of ACA. The material parameters (*MAT_COMPOSITE_MSC) are given as:

$$E_x = E_y = 24.1GPa \qquad E_z = 10.4GPa$$
$$\nu_{xy} = 0.12 \qquad \nu_{xz} = \nu_{yz} = 0.12$$
$$G_{xy} = G_{yz} = G_{zx} = 5.9GPa$$
$$S_{xT} = S_{yT} = 0.59GPa \qquad S_{xC} = S_{yC} = 0.35GPa$$
$$S_{FS} = 0.55GPa \qquad S_{FC} = 0.69GPa$$
$$S_{xy} = S_{yz} = S_{zx} = 48.3MPa \qquad S_{xCR} = S_{xCR} = 0.10GPa$$
$$S = 1.4 \qquad C = 0.1$$
$$\phi = 40^0 \qquad m = 4$$
$$\rho = 1783Kg/m^3$$

3. FUNCTIONAL ANALYSIS

The geometry and dimension of an ACA and the size and locations of the bolts are shown in Figure 4. The bolts are used to connect the ACA with a Ti plate, which represents a portion of the hull structure. This model is considered as the nominal design in this research. The projectile is assumed to be tungsten with spherical-shaped tip, and the dimension of the projectile is shown in Figure 4.



(a) Dimension of nominal design (b)Example layout of ACA

Figure 4. Dimension of the model

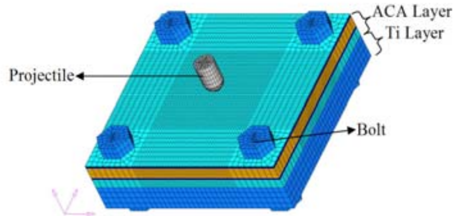


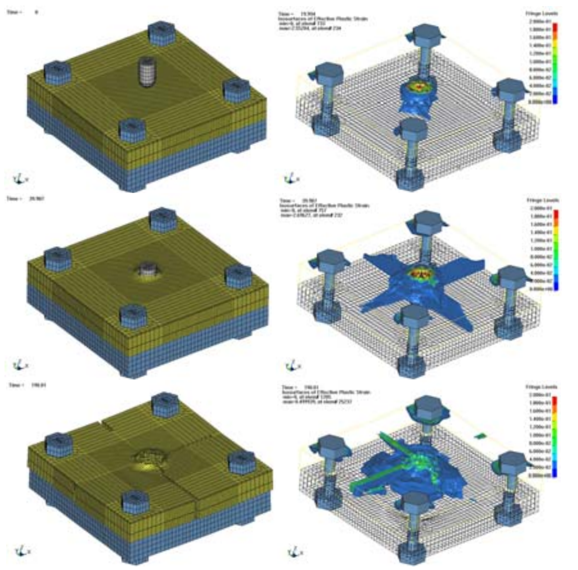
Figure 5. FEA mesh for ACA and projectile

The finite element mesh is shown in Figure 5. Altogether, 43,580 elements and 49,678 nodes are employed in the ACA and bolts model. The ACA and Ti layers are defined as simply in contact. It takes 2-6 hours to make one simulation on a 3.06GHz PC with 1.5G memory. It was found that LS-Dyna3D v970 is more stable than the previous versions, and satisfactory results can be obtained.

Simulation results were first obtained with different materials for projectile and different ACA designs. The materials for the projectile were considered to be steel or tungsten. Compared to steel, tungsten has much higher density. Other benefits with tungsten, such as high hardness and melting temperature, also contribute to the wide application of tungsten projectiles. Tungsten is therefore selected to be the material for the projectile in the following studies.

3.1 Pure-Ceramic Armor

Pure-ceramic armor was first considered for an initial study, and back plate was assumed to be made of Ti. The initial velocity of projectile was assumed to be 800m/s. The damage process for the armor/Ti structure is shown in Figure 6.



(a) (b)

Figure 6. The process of ballistic impact on all-ceramic armor/Ti assembly: (a)Damage to the ceramic tile; (b) Damage evolution and shear failure of bolts;

The velocity history of projectile predicted using the simulation tool is shown in Figure 7. The projectile penetrating process includes tip damages of the projectile, compression damage of the ceramic, ceramic damage due to reflective tensile wave in the opposite side of armor, radial cracking due to bending, fracture cone formation, crack expansion to the edges, plastic deformation of the back plate, and shear failure of the bolts.

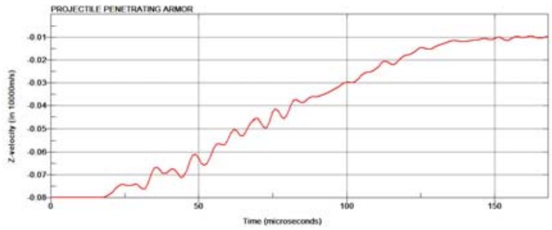


Figure 7. Change of projectile velocity with time

From the simulation result, it is seen that although the projectile did not penetrate the armor-metal structure, the bolts were broken due to expansion of broken armor and the deformation of the back plate. As a result, armor layer can fall off and lose protection against the subsequent attacks. Although no experiment was conducted to verify the current simulation results, researchers have reported that broken ceramic tiles can cause damages to the neighboring ceramic tiles. One example was reported in the work of Zaera et al. (Zaera et al., 2000) as shown in the right-top picture in Fig. 8. When the expansion force acts on the bolts against constraint force from metal plate, the bolts can be sheared to failure.

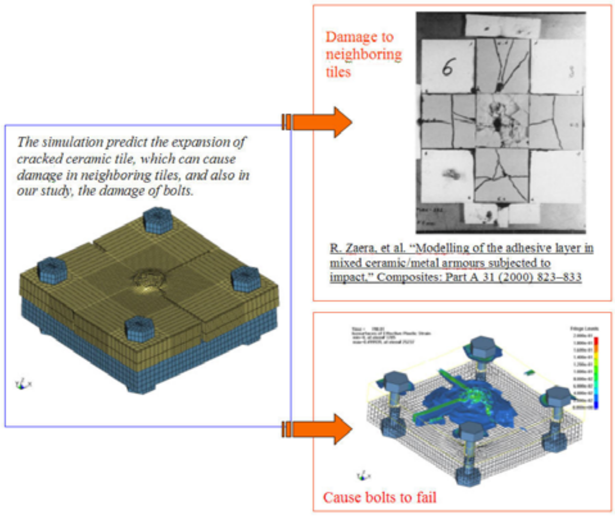


Figure 8. Ballistic impact on armor cause damage in bolts and neighboring tiles

Figure 9 illustrates the load acting on one of the bolts in the middle section with the description of the corresponding penetrating stages. It can be seen that bolts fail as a result of the expansion of broken tiles and the deformation of back plate. With the failure of bolts, structural integrity will be lost, and armor will fall off. With this analysis, the importance of joint (bolts) design becomes obvious.

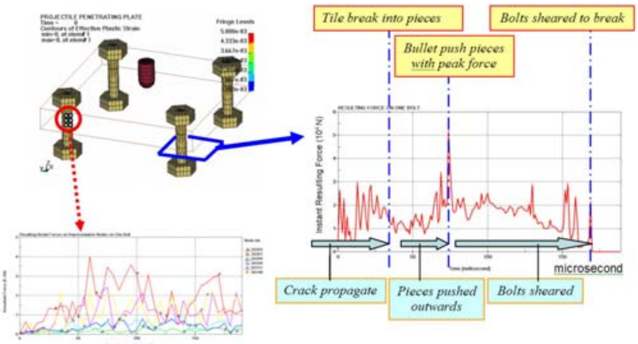


Figure 9. Force acting on one bolt during ballistic impact

3.2 Composite Armor

It is widely recognized that pure-ceramic armors have weakness, such as easy crack propagation and armor damage due to reflective shock wave on the back surface of the armors. Therefore, special advanced composite armors were developed to improve the performances. Ceramic-based armors were investigated, in which fabrics or fiber reinforced polymers were utilized. (e.g. Fink, 2002) The ballistic performances of joints connecting ACA and metal structure were evaluated as a comparison to pure-ceramic armors.

The same projectile with velocity of 800m/s is considered here.

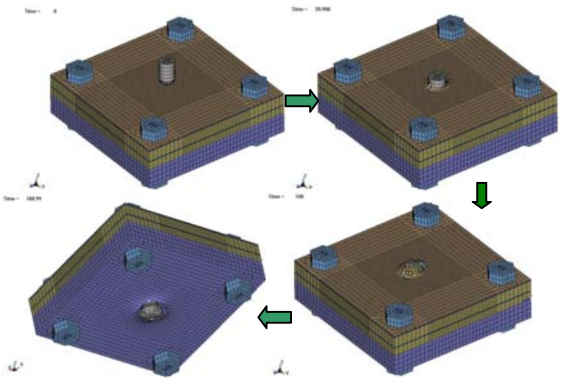


Figure 10. Penetration process of projectile through ACA and Ti substrate.

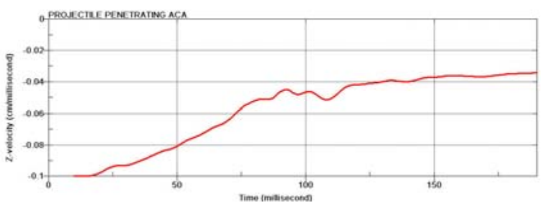


Figure 11. The changing velocity of projectile with time

From Figure 11, it can be seen that the projectile penetrates the ACA and Ti substrate, and the exist velocity of projectile is 370m/s. The thickness of ceramic layer is not enough to defeat the projectile in this example. It is also observed that because the ceramic layer did not crack and expand much, the bolts remained undamaged.

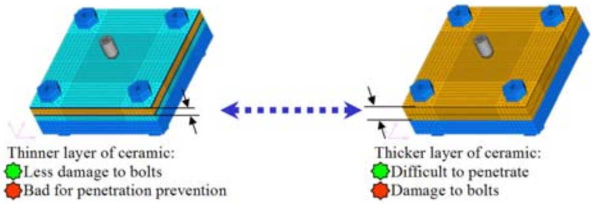


Figure 12. Influences of thickness of ceramic layer on the performances of armor and bolts

One important area of composite armor optimization is thickness optimization of each layer for better overall ballistic protection. The thickness changes influence the performance of bolts, which is illustrated in Figure 12. The thickness of ceramic layer should be decided according to the requirement of defeating the projectile. In this research, the projectile is assumed to remain the same. To prevent penetration, the thickness of ceramic layer needs to be large. As a result, the bolts will have a higher possibility of failure. Therefore advanced design methods are needed to improve the performances of joints in this situation. In the following sections, all-ceramic armor is considered as an example, but the design method developed can be applied to the advanced composite armors.

4. DESIGN PROBLEM

With the analyses described in the previous section, influences of ballistic impact on joints (bolts) can be identified, and objectives for joint (bolt) design can be determined. The joint design of ACA with the supporting structure should consider both (quasi-)static and ballistic loads. The design of joints with (quasi-)static loads can be completed with the design tools developed by us, which will not be reported here. The locations of bolts also have influences on the performances of bolts, but, in the current research, the bolt locations are assumed to be unchanged. The detailed bolt design, including configuration, dimension, and shape, is considered. The forces on a selected bolt are illustrated as cross-sectional forces in 10 cross sections, which are shown in Fig. 13. The overall forces on the bolts are large due to the expanding of the damaged armor.

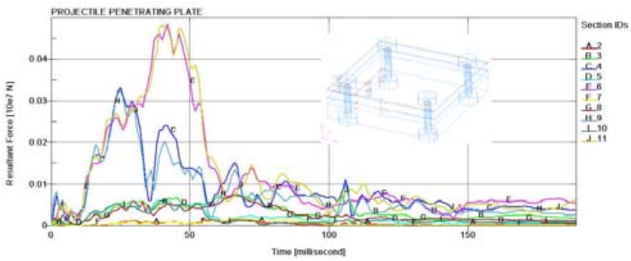


Figure 13. Cross-sectional forces inside ceramic layer

From the Figure 13, it is seen that the expanding force inside the ceramic layer is much higher in the lower half of the thickness. This can be attributed to the crack cone formation inside the ceramic and expansion of damage material in the lower half.

In Figure 14, a joint design problem is described. The blue area is the design domain, in which the geometry and shape of the reinforcement structure of the bolt will be laid out. Non-design domains, which represent the armor and plate, are shown in wire lines. The loads used for the design problem, which are acting on the non-design ceramic tile, are obtained from the aforementioned ballistic simulation.

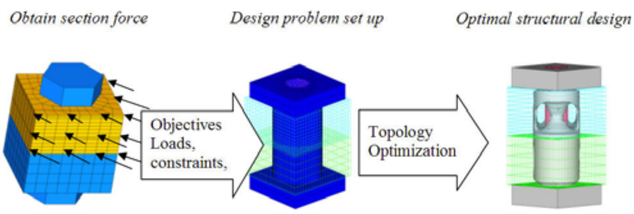


Figure 14. Detailed bolt design

With the post-processing program developed in this research, a preliminary design is obtained and it is shown in Figure 15. It is seen that the shape of new bolt design is responding to the shear loads acting on the bolts during the ballistic impact. An important feature of this new design is that it allows large shear deformation, which reduces the damage of the main bolt part due to the tile expansion. A simple larger-diameter design of the bolts will not have this feature, thus can not be used to prevent the bolt failure due to the large shearing force acting on the bolts.

From the Figure 15, it is seen that the optimum design from topology optimization has a relatively complicated geometry, which will pose a problem for the manufacturing and assembly processes. Simplification of the geometry is therefore necessary and the modified design is shown in right figure in Figure 15.

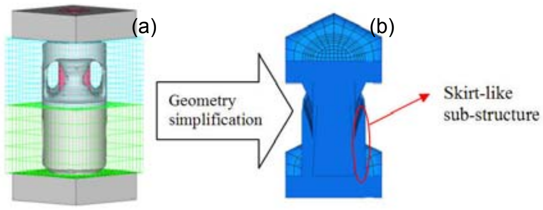
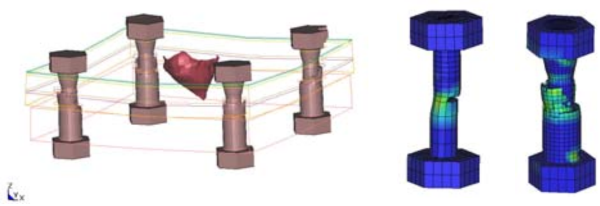


Figure 15. Designs from topology optimization design tools: (a) design from topology optimization tools; (b) modified design (cut in half to show the cross section shape)

Verification of the new design is carried out with the virtual prototyping. The results are shown in Figure 16(a). From this result, it can be seen that the bolts did not fail, although skirt-like tubular substructure of the bolt was crushed. In real applications, this substructure can be design as a separate part of the bolt for easy manufacturing. It is also found that there is another benefit from this new design: in normal condition, the tubular insert is strong enough to keep armor in position. When large forces act on the bolts due to ballistic impact, the liners undergo plastic deformation. The main structure of the bolts does not deform much, and the bolts will not break. As a result, the new bolts ensure connection between the armor and the metal structure in working condition and keep the structural integrity through local plastic deformation under ballistic impact.



(a) Final state of the impact *(b) Nominal and new bolts after impact*

Figure 16. Bolts remain unbroken and keep structural integrity

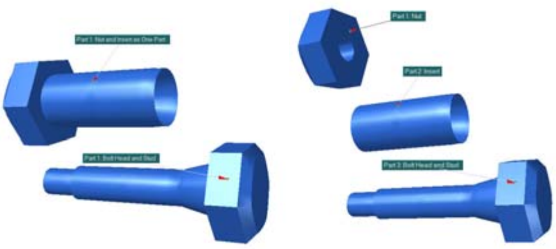
The final shapes of bolts for the nominal and improved designs under the ballistic impact are shown in Figure 16(b). It can be seen that for the new design, the main structures of bolts have much less plastic deformation and, as a result, the bolts don't break. The ballistic performances of bolts have been improved to keep structural integration under ballistic impact.

5. PHYSICAL PROTOTYPING

To identify the final shape of the optimal design from the topology optimization, manufacturability and assembly process have to be considered. An automatic post-

processor is developed, which also provides a function of automatic finite element mesh generation for numerical simulation. To identify the final structural geometry, firstly, the material value from topology optimization is understood as the uniform value for an element. Then, node material values are obtained with the same averaging method as that used for obtaining nodal stress in FEA post-processing. In this process, the elements with material are assigned with the value of 1, and void elements the value of 0. Smoothed nodal material values are in the range of [0,1]. The boundaries between material and holes are identified as contour surfaces of material value 0.5. As a result, patch-wise smooth boundaries can be found. More advanced algorithm with further surface smoothing and editing functions are being developed to further improve the design. This post-processor will be integrated in a user-friendly graphic environment for the overall design process. In this environment, manufacturing constraints will also be considered based on the method used to fabricate the structure.

The physical prototypes of aforementioned example design are fabricated with a rapid prototyping technique (Selective Laser Sintering-SLS). With the consideration of mass production, the bolts can be designed as two-piece or three-piece parts. The CAD file (STL format) from our automatic post-processor is depicted in Figure 17, together with physical prototypes. In the future, the performances of designs can be tested with the physical prototypes. It is seen that the proposed design system will improve greatly the efficiency of the armor joint design.



(a) CAD models from post-processor

(b) Rapid prototypes with Duraform™ Polyamide®

Figure 17. CAD model and final rapid prototypes

CONCLUSIONS

In this research, a design procedure based on an innovative Function-Oriented Material Design (FOMD) methodology is developed and demonstrated through a joint design example. The influences of ballistic impact on the joints (bolts) were investigated through virtual prototyping using a commercial code. It is seen that bolts may fail during the ballistic impact if not designed properly. Failures of bolts may result in losing the structural integrity of the ACA with the main structure of the vehicle. An optimal design problem has been then considered, and corresponding design procedures are developed to address the ballistic impact protection problem. Software tools are also developed for virtual prototyping and assisting physical prototyping. An integrated design environment is being developed for designer to participate effectively in the design process. The tools developed in this research will reduce the design cycle and thus help designers to meet the new challenges for military and civilian applications. It should be noted that the current research utilized the material parameters available in the literature, and geometry parameters are assumed for the demonstration purpose. The examples can be extended for real design problems with real engineering data.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support provided by the U.S. Army RDECOM.

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